VNIVERSITAT DE VALÈNCIA Facultat de Magisteri

Natural sciences for schoolteachers
LESSON 4:
Matter and its changes

Contents

Matter and its properties

Matter is anything that has mass and occupies space (volume).

All observable physical objects are made of matter.

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Matter and its properties

<u>Properties of matter</u>

There are **general properties** that do not enable one substance to be distinguished from another (***mass***, ***volume***, temperature).

Example: 1 kg of iron, water, air, etc.

There are also **specific properties** that enable one substance to be distinguished from another (***density***, boiling point, melting point, etc.).

Example: water (density=1 000 kg/m^3) boils at 100℃, whereas ethanol (density=789 kg/m^3) boils at 78℃.

Properties of matter: mass

An object's **mass** describes the amount of matter in it.

Image: Toby Hudson
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The unit of mass in the International System of Units is the **kilogram** (kg).

1 kg = 1 000 g	1 t = 1 000 kg	1 lb = 0.45 kg
1 g = 1 000 mg	1 @ = 12.78 kg	1 oz = 28 g

Properties of matter: volume

An object's **volume** describes the space it occupies.

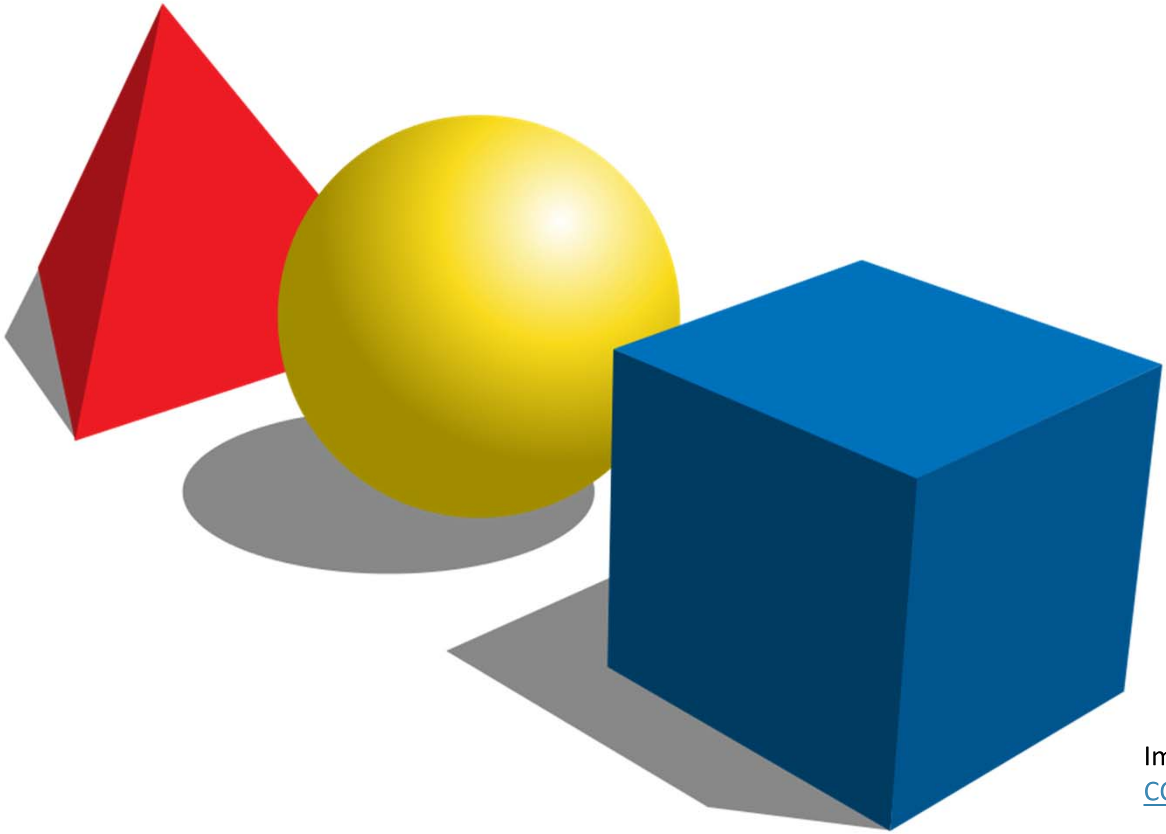
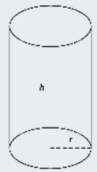
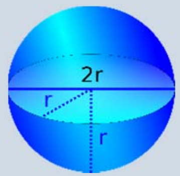
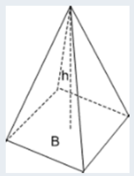
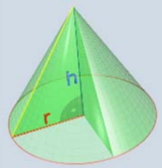


Image: Elisabethd/Mysid

The volume of any object can be calculated by multiplying its three dimensions: length, width and height.

Properties of matter: volume

Figure		Expression
cube		$V = l \cdot l \cdot l$
cylinder		$V = \pi \cdot r^2 \cdot h$
sphere		$V = \frac{4}{3} \cdot \pi \cdot r^3$
pyramid		$V = \frac{1}{3} \cdot B \cdot h$
cone		$V = \frac{1}{3} \cdot \pi \cdot r^2 \cdot h$

Properties of matter: volume

The unit of volume in the International System of Units is the **cubic metre**.

$$[V] = m^3$$

However, the most commonly used unit of volume is the **litre** (l), which equals to 1 cubic decimetre (dm^3).

$$1\,l = 1\,dm^3 = 0.001\,m^3$$

Properties of matter: density

The **density** of a substance is the amount of matter per unit volume.

Mathematically:

$$d = \frac{m}{V}$$

The unit of density in the International System of Units is the **kg/m³**.

Properties of matter: density

Substance	Density (kg/m³)
water	1 000
sea water	1 030
ice	917
oil	920
air	1 290
helium	1 790
aluminium	2 700
iron	7 860
glycerin	1 260
ethanol	806

States of matter

By modifying the temperature and surrounding pressure of any substance, different **states of matter** can be obtained:

solid **liquid** **gas**

Image: Darren Hester

Image: José Manuel Suárez

Image: Briain

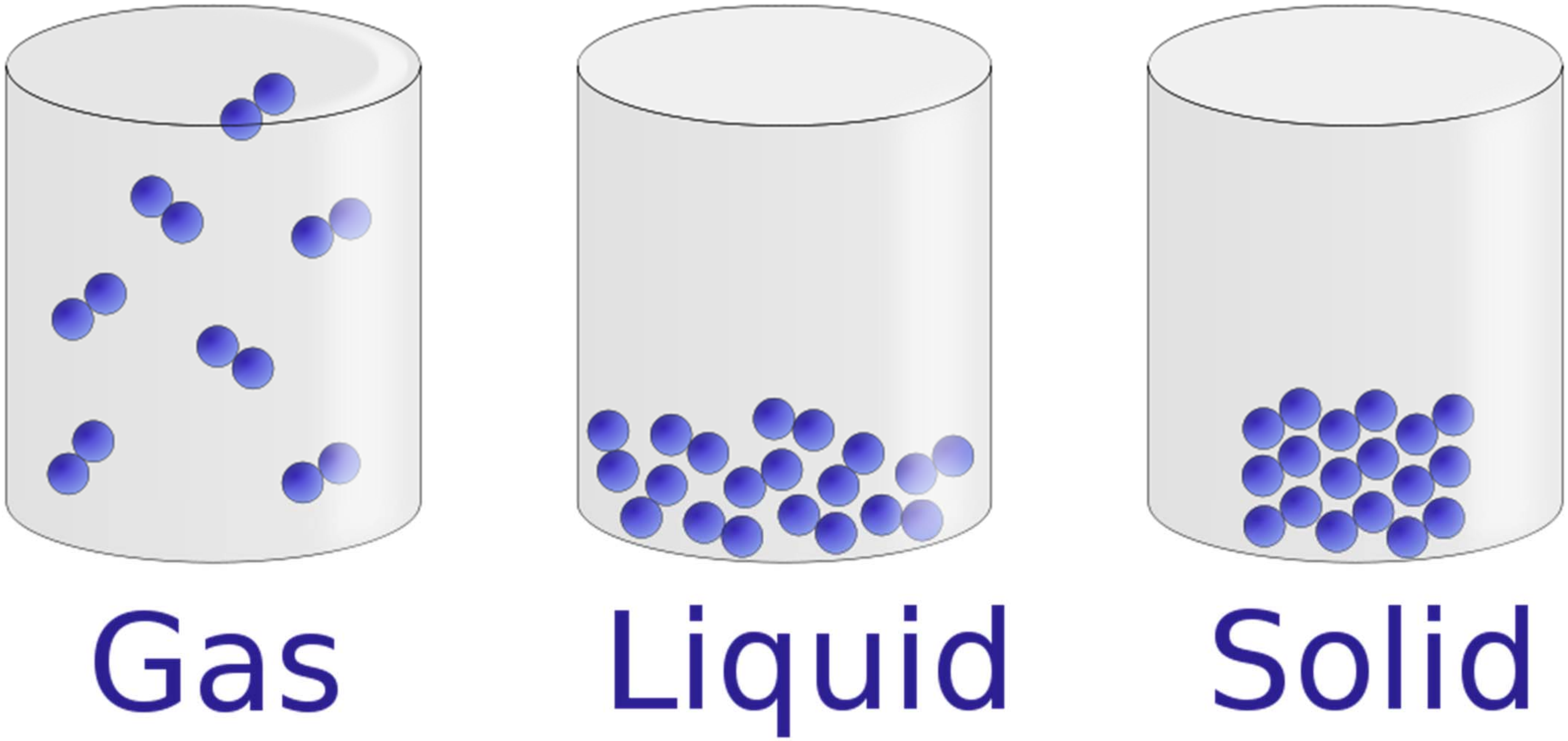
States of matter

To explain the properties of matter we use the **kinetic theory**, which is mainly based on the following assumptions:

1. ***Matter consists of very small particles, and between them there are empty spaces.***
2. ***These particles are in constant motion.***
3. ***There are forces of attraction between particles.***
4. ***The separation between particles depends on the state of matter.***

This theory was developed by several scientists (Daniel Bernoulli, August Krönig, Rudolf Clausius, etc.) during the 18th and 19th centuries, based on studies of the physical behavior of gases (***kinetic theory of gases***), and then generalising it to other states of matter (***kinetic theory***).

States of matter



States of matter: solid

Solids have a ***definite shape*** and a ***nearly constant volume***, since the particles that form them are strongly bonded and very close to each other.

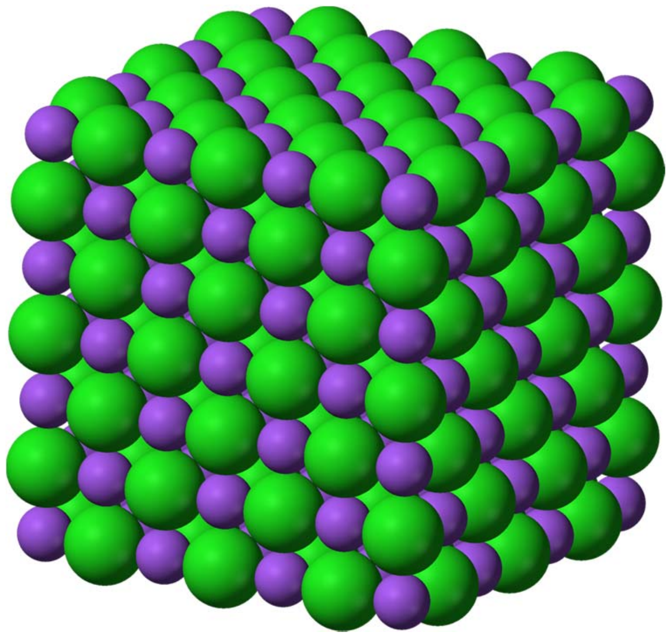


Image: Benjah-bmm27

The particles that form solids can only vibrate or oscillate about fixed positions.

States of matter: liquid

Liquids have a ***variable shape***, taking the shape of their container, since the particles that form them are less bonded and not so close to each other.

Image: zhouxuan12345678

States of matter: liquid

Liquids have a ***nearly constant volume***, since the particles that form them are relatively close together.

Example: If we cover the orifice of a syringe filled with water, and we push the plunger, it will not advance.

Image: I woz ere

States of matter: liquid

Liquids can ***flow***, since the particles that form them do not occupy fixed positions and move freely. The motion of the particles is random, although forces of attraction between particles makes them move simultaneously.

Image: Javier Morales

Matter and its properties

<u>States of matter: gas</u>

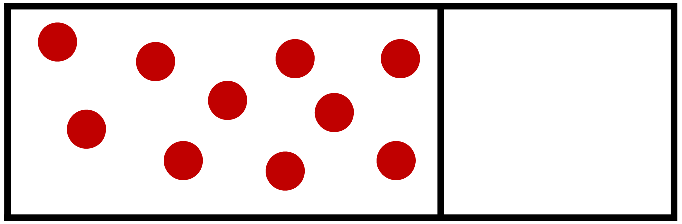
Gases *do not have a definite shape nor a constant volume*.

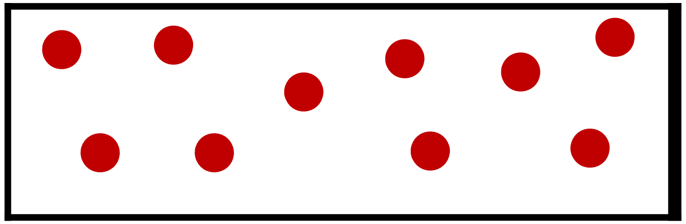
Image: mwwile

Gases take the shape of their container. In addition, gases tend to fill their container since the particles that form them are not bonded and move freely - randomly colliding with each other and the container walls.

States of matter: gas

The ***volume*** of gases is easily ***changed*** because they can be ***compressed*** and ***expanded***.





Expansion: when increasing the volume, the gas particles are further apart.

Compression: when decreasing the volume, the gas particles are closer together.

States of matter: gas

Gases, as liquids, can ***flow***, since the particles that form them do not occupy fixed positions and can move freely.

Image: Macluskie

Both liquids and gases are called **fluids**.

Changes in states of matter

Changes in states are the processes in which matter changes from one state to another without changing its composition.

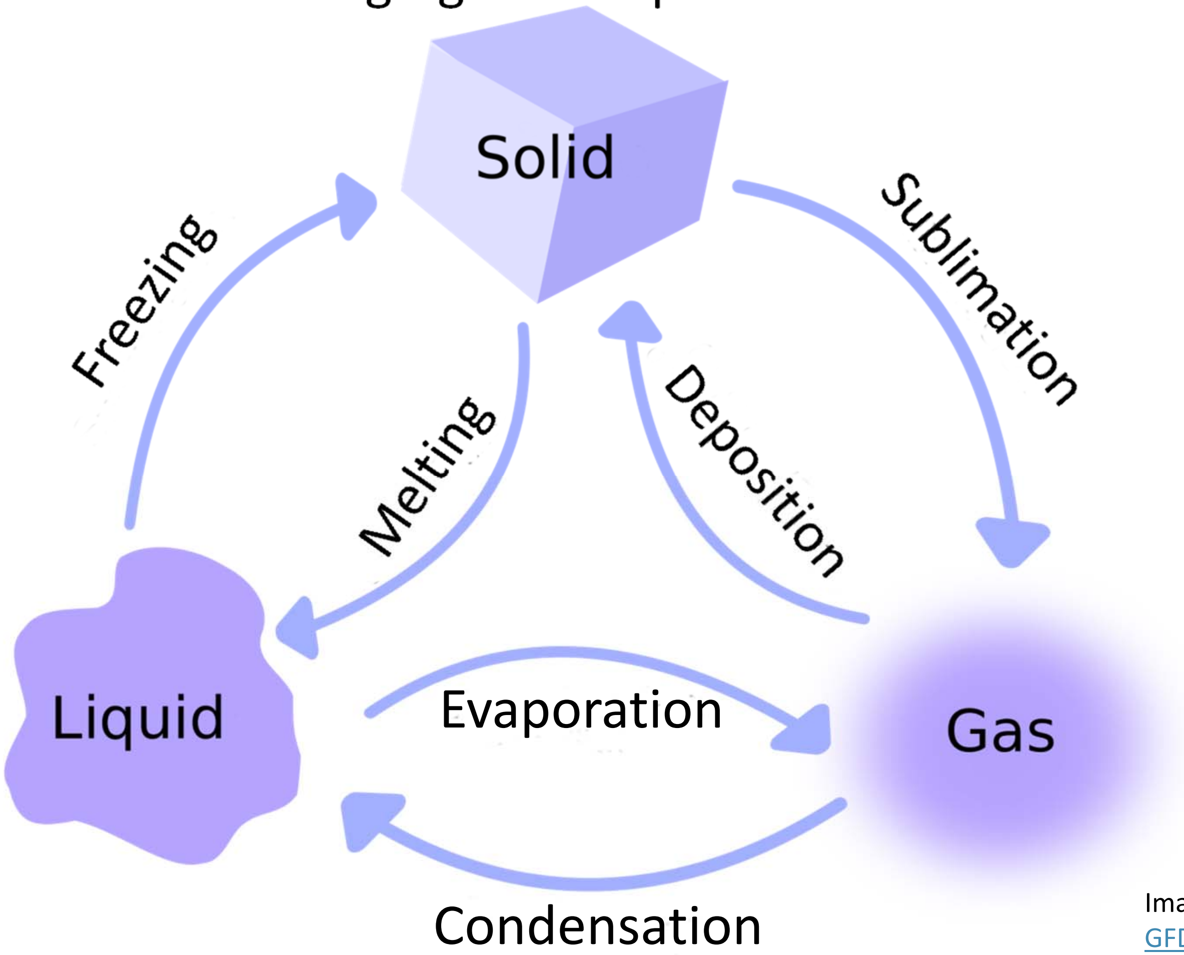


Image: Josell7/A.R. Esteve
GFDL

Changes in states of matter

The main **changes in states of matter** are:

- If a solid is heated, it eventually becomes liquid. This process is called **melting**. The ***melting point*** is the temperature at which solids melt. Each substance has a specific melting point. The reverse change is called **freezing**.
- If a liquid is heated, it eventually becomes a gas. This process is called **evaporation**. The ***boiling point*** is the temperature at which liquids evaporate. Each substance has a specific boiling temperature. The reverse change is called **condensation**.
- The change from solid to gas is called **sublimation,** and the change from gas to solid is called **deposition**.

The atom

Some ancient Greek philosophers established two different theories:

1) **Atomism** (***Democritus***, 460-370 BC), which stated that if we divide a fragment of matter into smaller pieces, we will end up finding an indivisible piece. These small indivisible particles were called ***atoms*** (Greek for *"uncuttable"*).

2) **Continuity theory** (***Aristotle***, 384-322 BC), which stated that matter is continuous (i.e., it can be divided endlessly) and is made of small amounts of the four elements: ***earth***, ***fire***, ***water*** and ***air***.

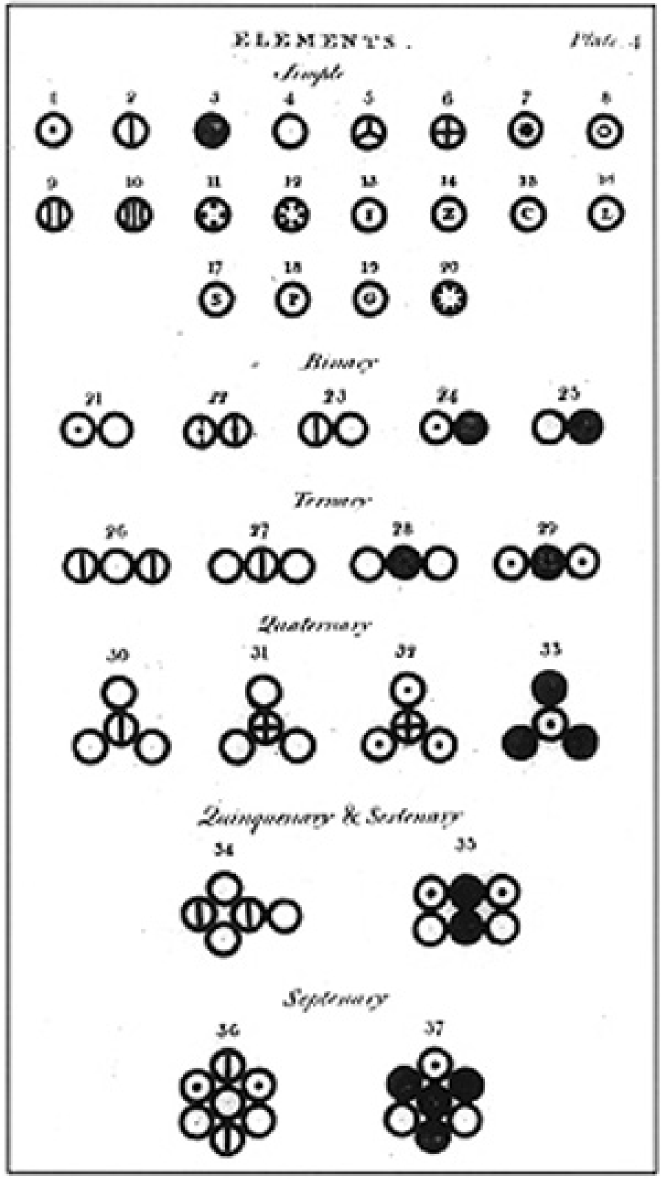
However, today we all accept that ***matter is not continuous but formed by particles***.

The atom

Dalton model

In 1808, **John Dalton** (1766-1844) published his atomic theory, which was based on Democritus' ideas but using a series of scientific laboratory experiments.

This atomic model explained most of the chemistry of the late 18th and early 19th centuries.

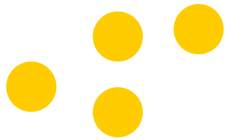


A New System of Chemical Philosophy (John Dalton , 1808).

The atom

Dalton model

All matter is made of extremely small particles called atoms, which are indivisible and indestructible.



Gold atoms

Image: Alchemist-hp (www.pse-mendelejew.de)
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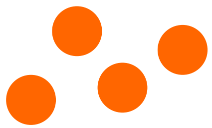


Copper atoms

Image: Jonathan Zander
CC BY-SA 3.0

Dalton model

All atoms of a given element are identical in mass and properties; atoms of different elements differ in mass and other properties.

1	2	6	8
H	**He**	**C**	**O**
1,008	4,003	12,011	15,999

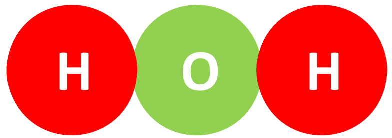
The atom

<u>Dalton model</u>

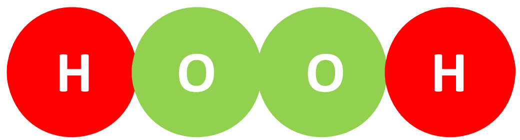
Chemical compounds are formed by a combination of two or more different kinds of atoms in simple whole-number ratios.

Example:

All molecules of water are identical, formed by the combination of 2 atoms of hydrogen and 1 atom of oxygen.



All molecules of hydrogen peroxide are identical, formed by the combination of 2 atoms of hydrogen and 2 atoms of oxygen.



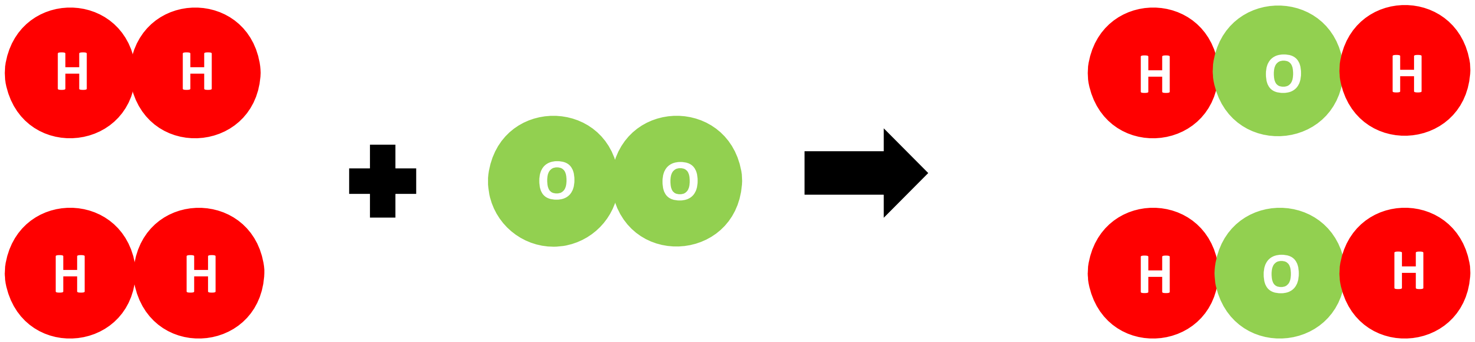
The atom

Dalton model

In chemical reactions, atoms are combined, separated, or rearranged, but they do not disappear nor are transformed.

Example:

Hydrogen and oxygen react to produce water. In this chemical reaction, the atoms of hydrogen and oxygen are the same at the beginning and the end. How they are bonded together is the only thing that changes.



<u>Thomson model</u>

In the early 19th century, several ***electrical phenomena*** were discovered which showed that matter could gain or lose ***electrical charges***, which should be somehow inside the atoms.

If this was true, Dalton's atomic model was wrong, since it stated that atoms were indivisible and indestructible.

Thomson model

In 1897, **J. J. Thomson** (1856-1940) conducted several experiments in electrical discharge tubes, which are glass containers filled with a gas at very low pressure with two metal electrodes through which an electric current at high voltage is applied.

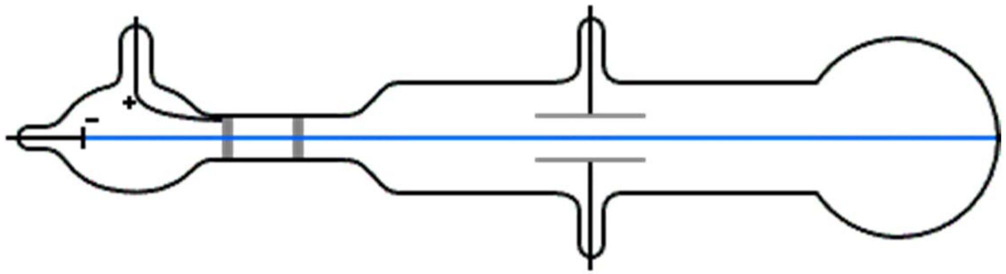


Image: Kurzon

J. J. Thomson discovered that rays were emitted from the negative electrode to the positive electrode (***cathode rays***), and when he studied the particles that formed these rays, he observed that they were always the same, whatever the gas inside the tube was. Therefore, he concluded that inside all atoms exist negatively charged particles, which he called **electrons**.

Thomson model

In 1904, J. J. Thomson suggested that the atom is composed of ***negatively charged particles (electrons) distributed in a uniform 'cloud' of positive charge***.

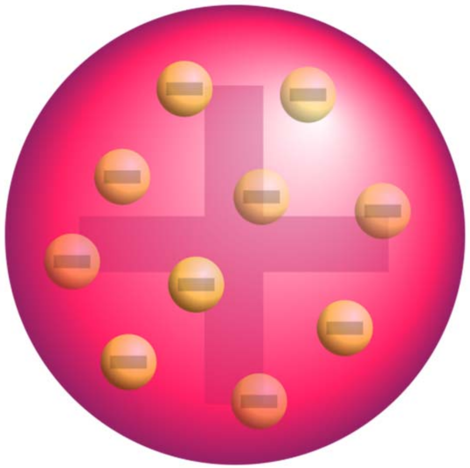


Image: Fastfission

This model explains how ions are formed: when an atom loses electrons, it acquires a positive net charge, and when an atom gains electrons, it acquires a negative net charge.

Thomson model

Thomson's atomic model is also known as the ***'plum pudding model'*** since the electrons are distributed inside the atom in a uniform 'cloud' of positive charge.

Image: Lachlan Hardy

Rutherford model

In 1911, **Ernest Rutherford** (1871-1937) studied the deflection of a beam of ***alpha particles*** (positive particles from a radioactive material) when it strikes a thin metal foil.

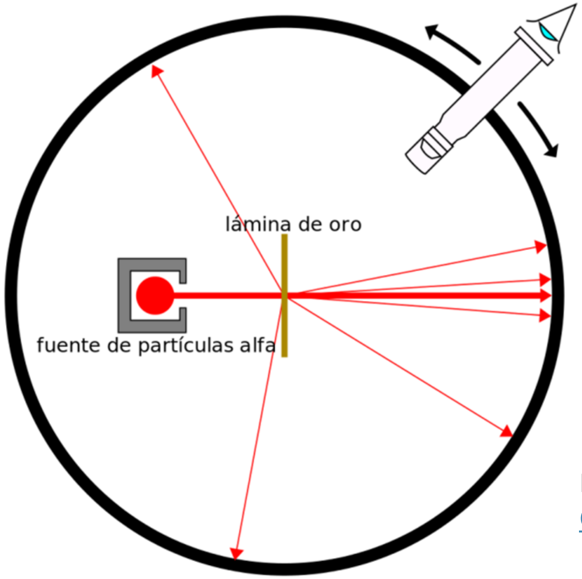


Image: Kurzon
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According to Thomson's atomic model, the alpha particles would pass through the foil with negligible deflection. Nevertheless, although most of them did so, a small portion of the alpha particles were heavily deflected.

The atom

Rutherford model

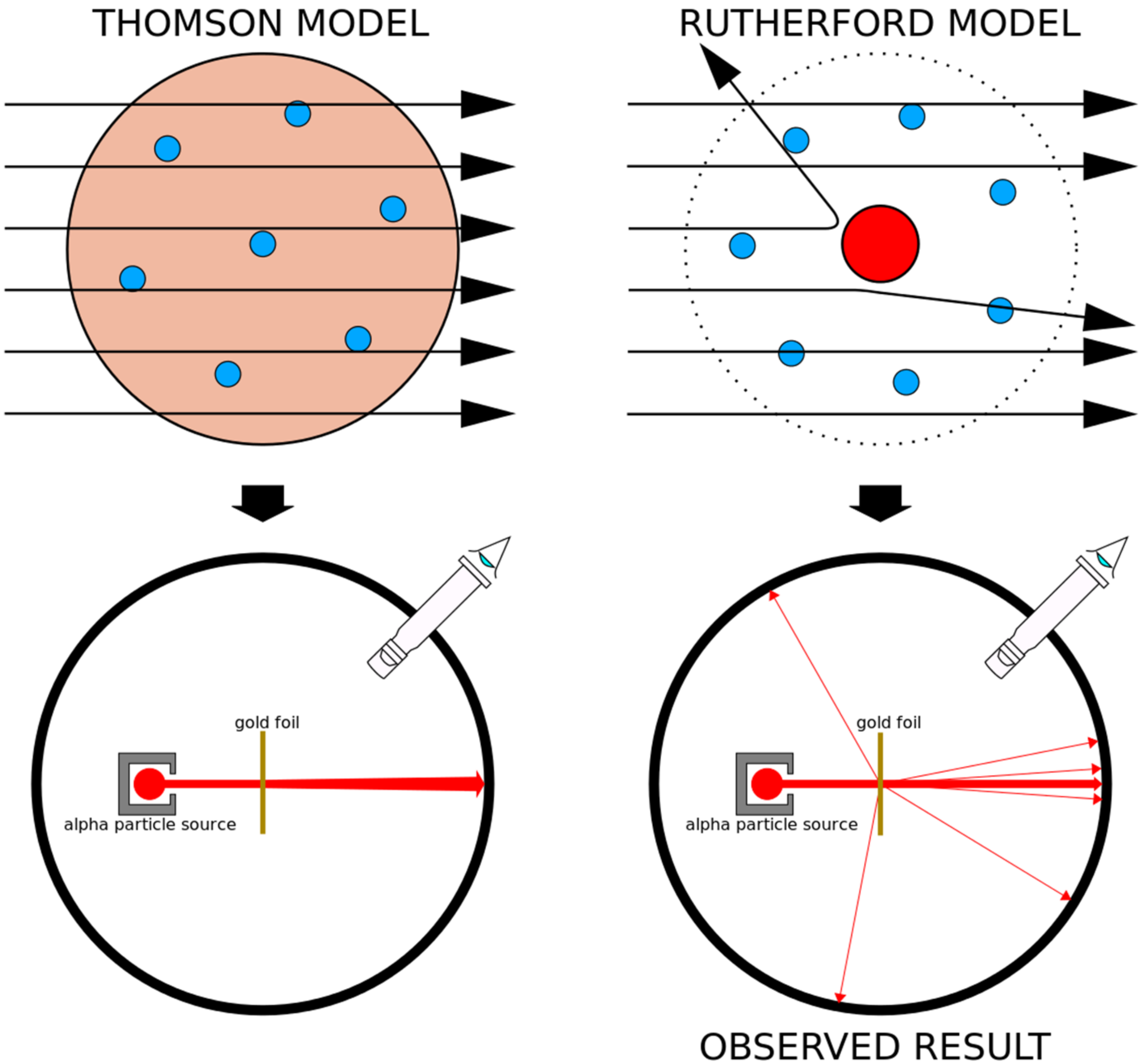
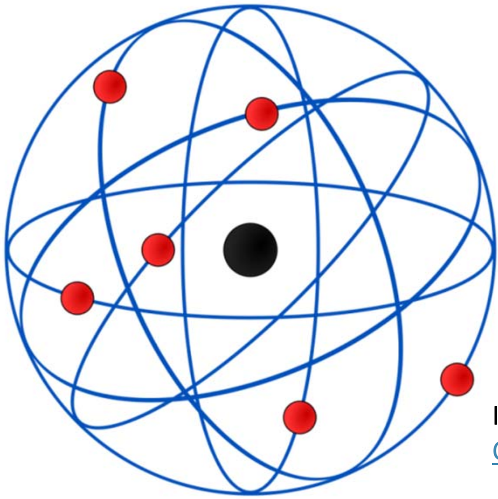


Image: Kurzon

Rutherford model

Rutherford's atomic model establishes that the atom is composed of:

- a relatively tiny **nucleus** where much of an atom's mass and positive charge are concentrated.
- an external ***'cloud'*** which consists of electrons orbiting around the nucleus at high speed.



The radius of the atom is 10 000 times greater than that of the nucleus. Therefore, most of the atom is empty.

The atom

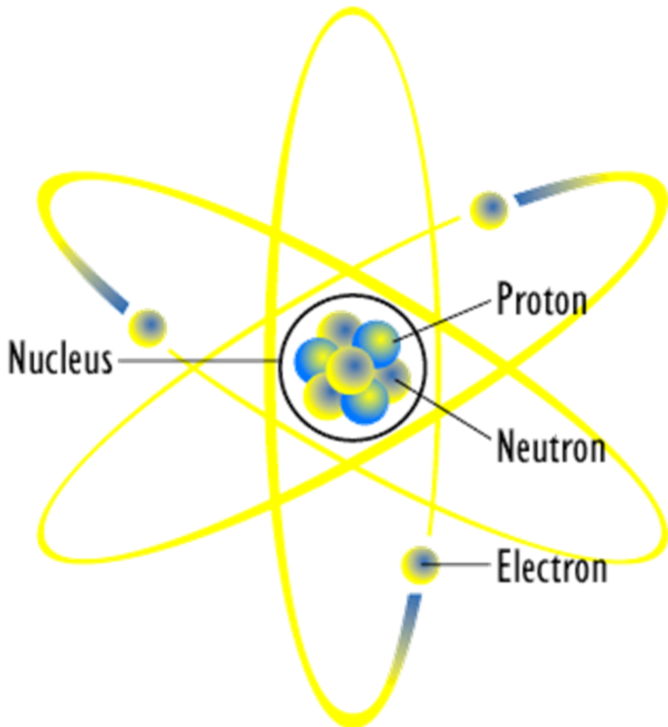
Rutherford model

The nucleus of the atom is composed of:

- **protons**, which are particles whose charge is the same as the electron but positive, and their mass is 1 837 times greater.
- **neutron**, which are particles without net charge, and their mass is slightly greater than that of protons.

The ***positive charge*** of ***protons*** is compensated by the ***negative charge*** of ***electrons***, and thus the ***atom*** is electrically ***neutral***.

Therefore, the nucleus contains the same number of protons as the number of electrons in the atom.

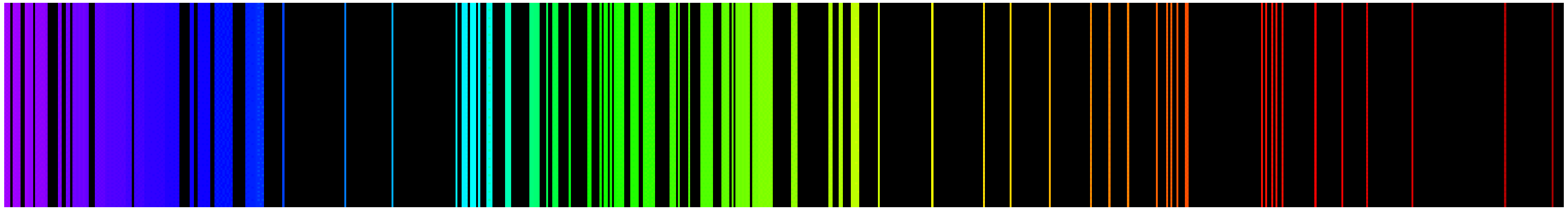


Bohr model

Rutherford's atomic model could not explain the specific ***emission spectra*** of chemical elements.

Emission spectrum of hydrogen.

Image: Merikanto/Adrignola



Emission spectrum of iron.

Image: Nilda

The emission spectrum of a chemical element is the set of frequencies of the electromagnetic radiation emitted by the atoms of that element in a gas state. The emission spectrum of each element is unique.

Bohr model

In 1913, **Niels Bohr** (1885-1962) proposed an atomic model in which ***electrons*** can only orbit the nucleus stably in certain circular ***orbits***. These orbits are associated with definite energies (***energy levels***).

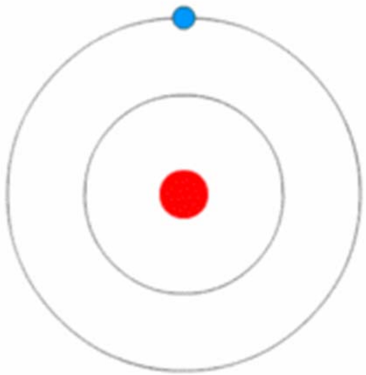


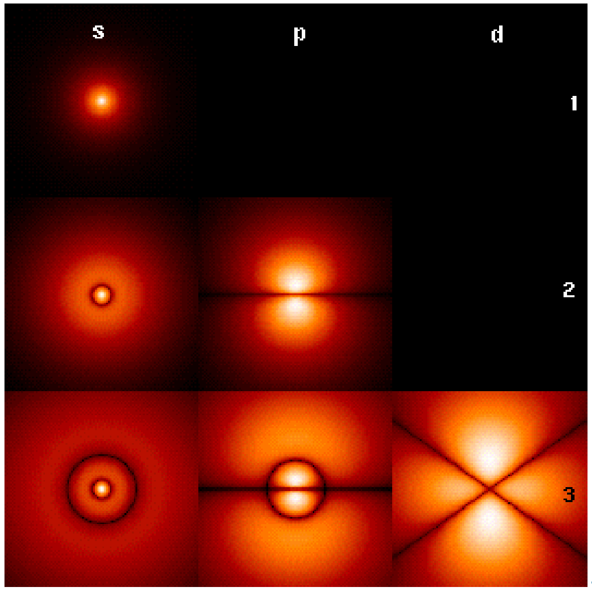
Image: Kurzondddd

Electrons can only gain and lose energy by jumping from one allowed orbit to another, absorbing or emitting electromagnetic radiation.

Schrödinger model

Although Bohr's atomic model works well for the hydrogen atom, small variations in the emission spectra were observed for other atoms that this model could not explain.

In 1924, **Erwin Schrödinger** proposed the ***quantum mechanical model of the atom***, which states that electrons orbiting the nucleus could not be considered to have an exact location.



Density of location probability of an electron for the first energy levels.
Imagen: Falcorian

The atom

Atomic structure

Since the 1970s we know that protons and neutrons are particles composed of elementary particles called **quarks**.

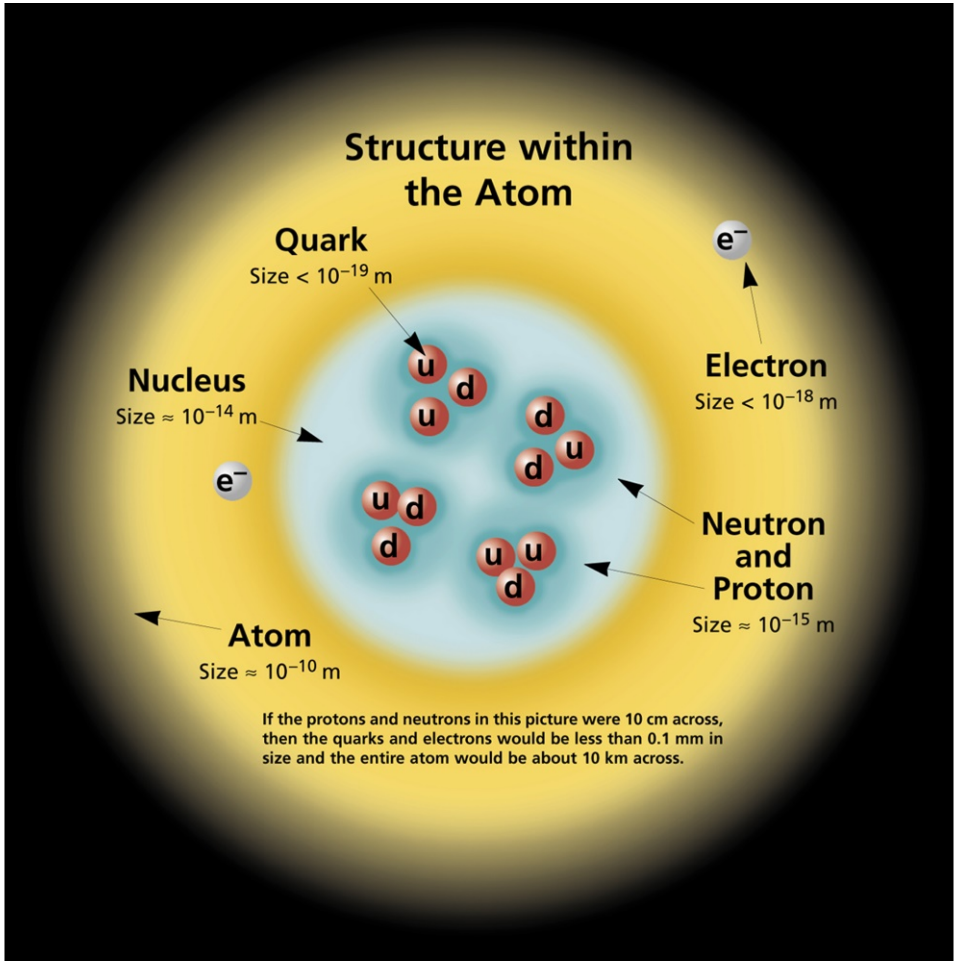


Image: The Contemporary Physics Education Project

Atom identification: atomic number and mass number

The properties of an atom are given by the number of particles that it contains.

$$^{A}_{Z}X$$

The **atomic number** (Z) indicates the number of ***protons*** found in the nucleus of an atom. It uniquely identifies a chemical element.

The **mass number** (A) indicates the total number of particles found in the nucleus of an atom, i.e., the total number of ***protons*** and ***neutrons***.

For example, the element $^{2}_{1}H$ *has an atomic number of Z = 1 (i.e., it has 1 proton in the nucleus) and a mass number of A = 2 (i.e., it has 2 particles in the nucleus, and since Z = 1 , it has 1 proton and 1 neutron).*

Atom identification: ions

A **cation** is an atom with a net positive charge, caused by the loss of electrons.

$$ {}_{1}^{1}H^{+1} $$

An **anion** is an atom with a net negative charge, caused by the gain of electrons.

$$ {}_{1}^{1}H^{-1} $$

Atom identification: isotopes

Atoms which have the same number of protons but differ in the number of neutrons are called **isotopes**.

The isotopes of a chemical element have the same atomic number (Z), but different mass numbers (A).

Most chemical elements have more than one isotope. For example, carbon is presented in nature as a mixture of three isotopes: C-12, C-13 and C-14.

If the relationship between the number of protons and neutrons is not appropriate for nuclear stability, the isotope will be radioactive (**radioisotope**), and it will spontaneously decay into a more stable atom by emitting radiation.

Pure substances and mixtures

Matter can be classified into:

- **Pure substances -** which have characteristic properties that enable us to clearly distinguish one substance from other (e.g: density, melting point, boiling point, etc.).

- **Mixtures -** which are made up of two or more pure substances, the properties of which are retained.

Pure substances and mixtures

Pure substances

Pure substances have constant chemical composition and characteristic properties.

Example: water always has the same properties and the same ratio of hydrogen and oxygen (H_2O). If these properties and ratio change, it will be a different substance.

They cannot be separated into components by physical separation methods.

Pure substances can be classified into: **elements** and **compounds**.

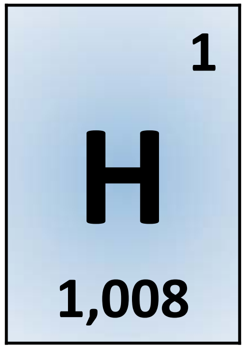
Pure substances and mixtures

Pure substances

Elements are pure substances that cannot be separated into components.

They consist of only one kind of ***atom***.

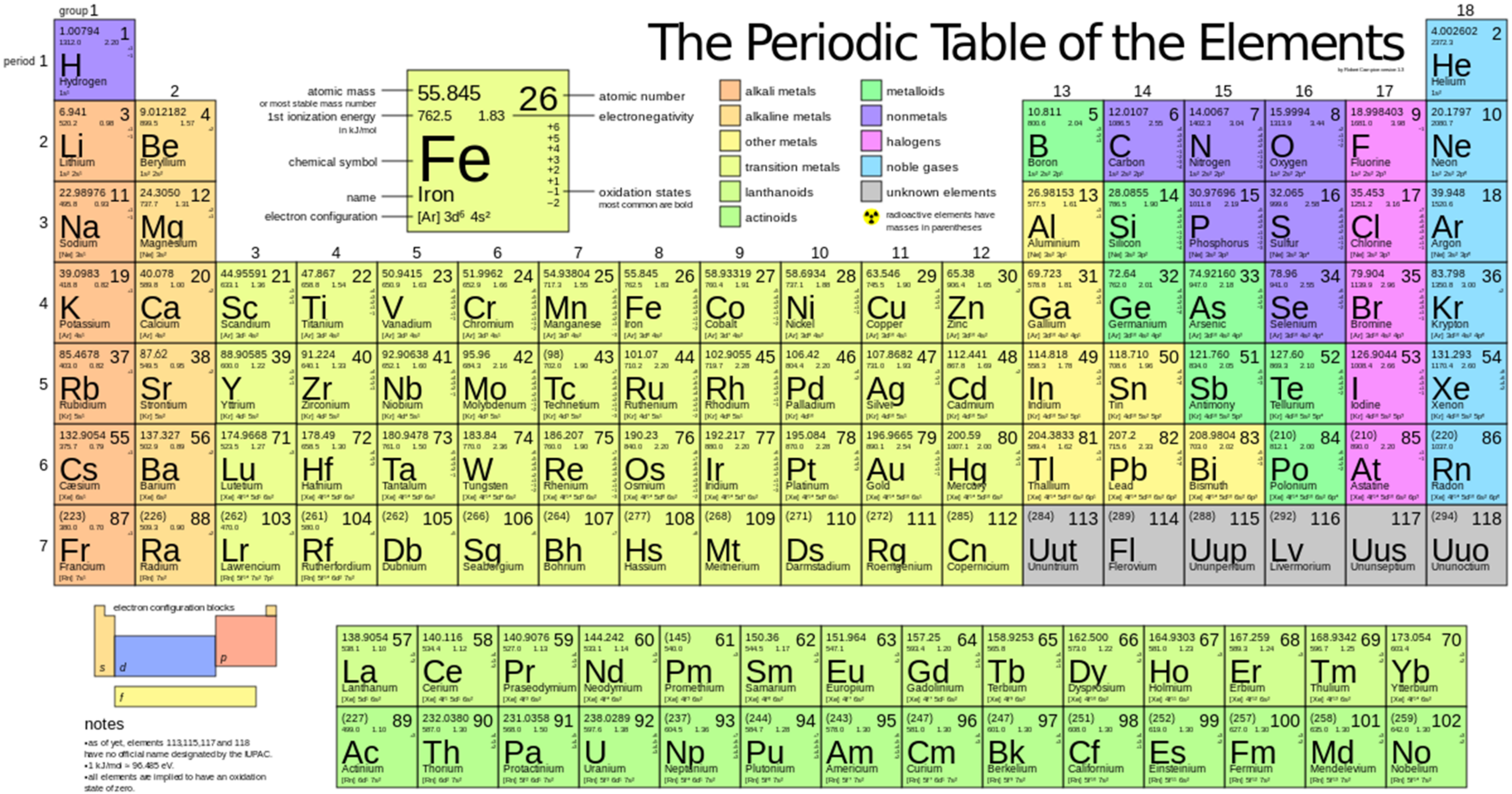
Example: hydrogen



There are 118 known elements that have been identified, of which 94 occur naturally on Earth, and the remaining 24 have been produced artificially since they are all radioactive and have very short half-lives.

Pure substances and mixtures

Pure substances



Pure substances and mixtures

<u>Pure substances</u>

Compounds are pure substances that can be separated into components (elements) by chemical reactions.

They are composed of two or more different atoms (***molecules***).

Example: water (H_2O)

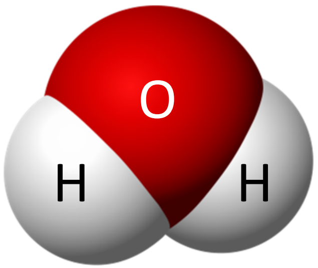


Image: Dbc334/Jynto/A.R. Esteve

Pure substances and mixtures

Mixtures

Mixtures are made up of two or more pure substances, the properties of which are retained.

The physical properties of a mixture may be different from those of the components, and they will depend on the mixture's composition.

Mixtures can be separated into components by physical separation methods.

Mixtures can be classified into: **heterogeneous mixtures** and **homogeneous mixtures**.

Mixtures

A **heterogeneous mixture** is a mixture in which its components can be seen by the naked eye or optical methods.

Example: granite, water and oil ...

Image: David Monniaux

Image: Victor Blacus

Pure substances and mixtures

Mixtures

A **homogeneous mixture** is a mixture in which its components cannot be seen by any means. This kind of mixture is also called ***dissolution***.

Example: salt water, steel, air ...

Image: S nova

Image: wlodi

Pure substances and mixtures

Mixtures

There are mixtures that look like homogeneous mixtures but, in fact, are heterogeneous mixtures. These mixtures are called **colloids**.

Colloids are usually quite unstable, and tend to aggregate spontaneously.

Examples: milk, mayonnaise, blood ...

Image: Bestalex

Image: jules

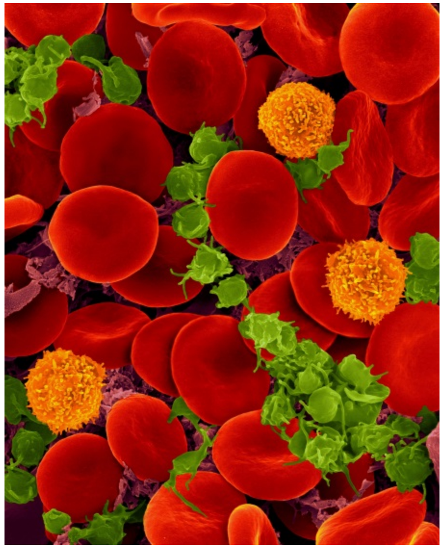


Image: Dennis Kunkel Microscopy, Inc.

Separation of mixtures

The different components of heterogeneous mixtures can be separated by mechanical means. However, the components of homogeneous mixtures are more difficult to separate.

Heterogeneous mixtures	Homogeneous mixtures
Sieving	Crystallisation
Filtration	Distillation
Decantation	…
Magnetic separation	
…	

Pure substances and mixtures

Separation of heterogeneous mixtures

Sieving is a technique for separating ***solid heterogeneous mixtures*** where the components have ***different sizes***.

Example: The sieve is used to separate solid components that have different sizes (such as sand and pebbles, or flour and grain).

Pure substances and mixtures

<u>Separation of heterogeneous mixtures</u>

Filtration is a technique used for separating ***heterogeneous mixtures*** of ***solids*** and ***liquids***, where the solid is not soluble in the liquid.

Example: sand and water, coffee and water ...

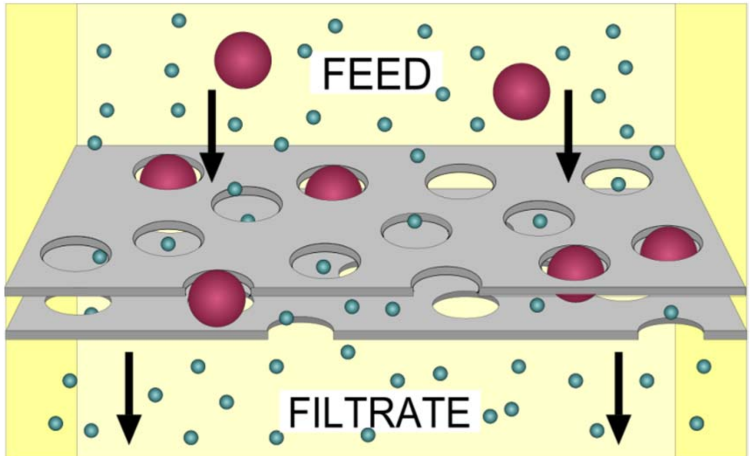


Image: Wikiwayman at English Wikipedia

Since the particles of the solid are much larger than those of the liquid, the solid will be retained by the filter, while the liquid will easily pass through.

Separation of heterogeneous mixtures

Decantation is a technique for separating ***heterogeneous mixtures*** of ***liquids with different densities that do not mix***.

Example: water and oil, sewage ...

A ***separatory funnel***, which has a valve at the bottom, is commonly used in this technique. When the two liquids are clearly not mixed, the valve is opened to allow the fluid with the highest density to exit.

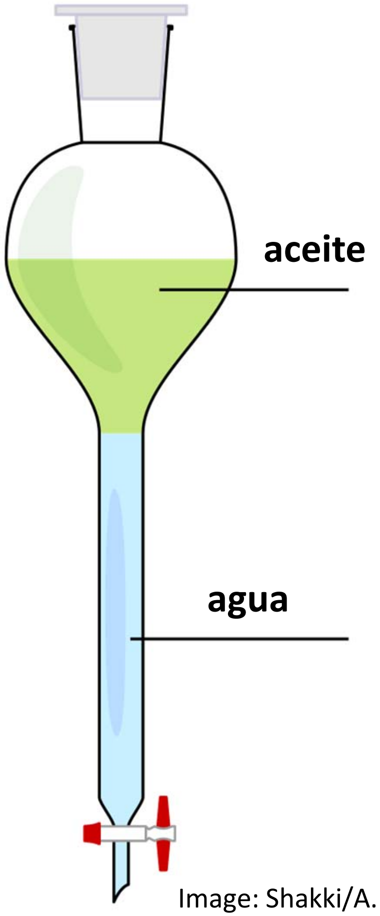


Image: Shakki/A.R. Esteve

Pure substances and mixtures

Separation of heterogeneous mixtures

Magnetic separation is a technique used for separating ***heterogeneous mixtures*** of ***solids*** where some of the components are ***ferromagnetic***, i.e., they are attracted to ***magnets***.

Example: When a magnet is placed near the mixture, the ferromagnetic components can be easily removed.

Pure substances and mixtures

<u>Separation of homogeneous mixtures</u>

Crystallisation is a technique used for separating ***homogenous mixtures*** of a ***solid*** dissolved in a ***liquid***.

This technique consists in evaporating the liquid, and thus solid crystals precipitate from the dissolution.

Example: water and salt

Image: Jon RB

Separation of homogeneous mixtures

Distillation is a technique used for separating ***homogenous mixtures*** of ***liquids*** which have different boiling temperatures.

Example: This technique is used for separating mixtures of water and alcohol. Since alcohol is more volatile than water, it is the first substance to boil and evaporate. When it cools, it condensates in a different flask.

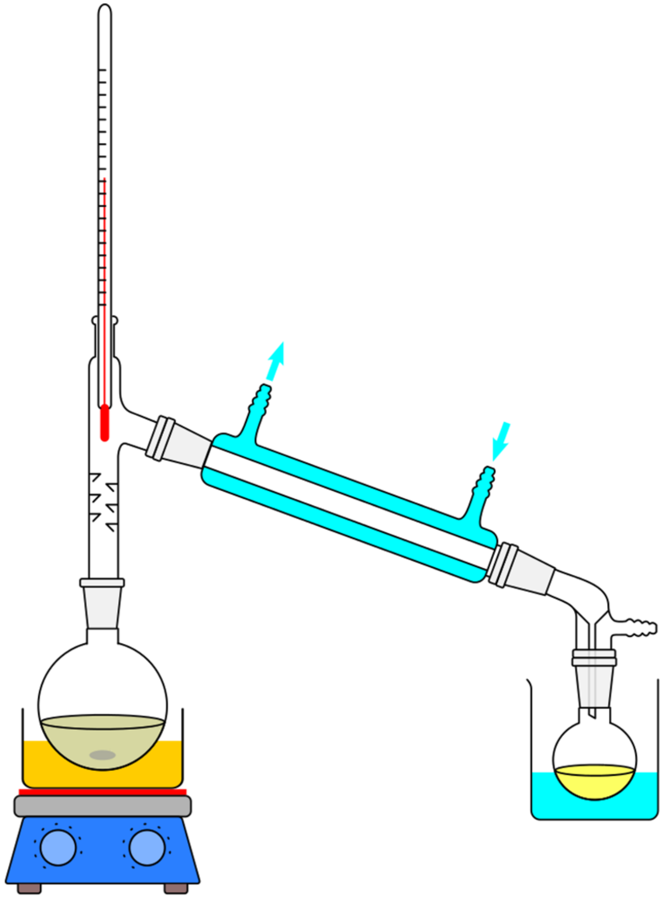


Image: Quantockgoblin/Slashme/A.R. Esteve

Changes in matter

There are constant transformations in nature.

Image: zen whisk
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These changes can be:

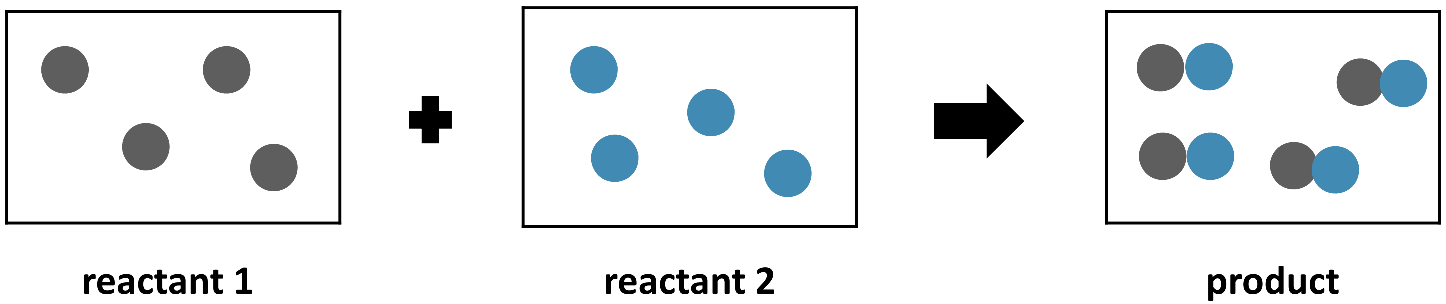
- **Physical transformations**: the substance's appearance changes, but not its nature (e.g: changes in states of matter).
- **Chemical transformations**: the substance's nature changes, turning into a new substance with different properties (e.g: combustion, oxidation).

Chemical reactions

A chemical reaction is the process of transformation of a set of chemical substances.

- The substances at the beginning of a chemical reaction are called **reactants**.

- The substances formed during the chemical reaction are called **products**.



Chemical reactions

Chemical reactions involve the forming and breaking of **chemical bonds** between atoms, and thus the atoms of the reactants and the products will be bonded differently.

Therefore, the physical and chemical properties of the reactants and the products are different.

Example:

$$Cl_2 + H_2 \rightarrow 2HCl$$

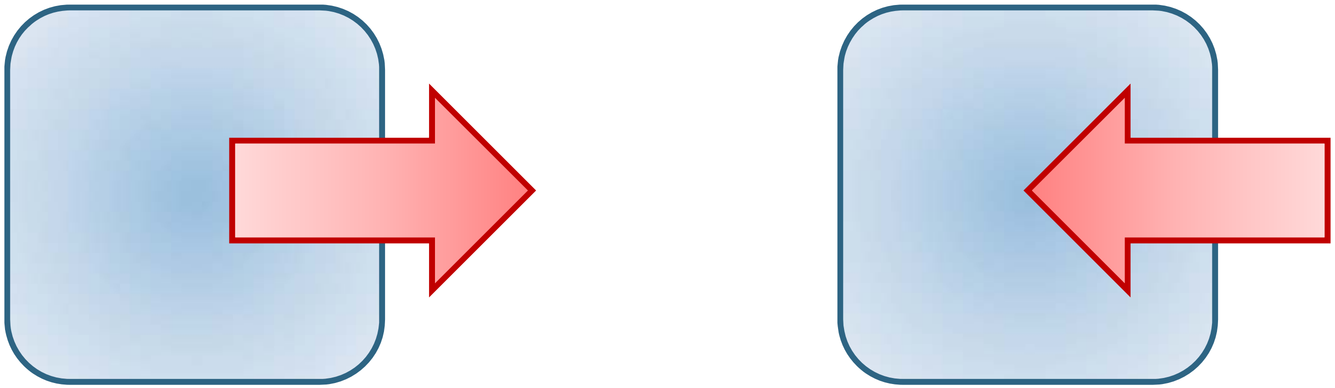
The number and kind of atoms in a chemical reaction is always the same, and thus the mass of the products will be the same as the mass of the reactants (***principle of mass conservation***).

Changes in matter

<u>Chemical reactions</u>

In any chemical reaction there is an exchange of energy, so that chemical reactions can be classified into:

- **Exothermic reactions**, which release energy (e.g.: combustion).
- **Endothermic reactions**, which absorb energy (e.g.: ozone in Earth's atmosphere is produced from UV radiation).



EXOTHERMIC REACTION
releases energy

ENDOTHERMIC REACTION
absorbs energy

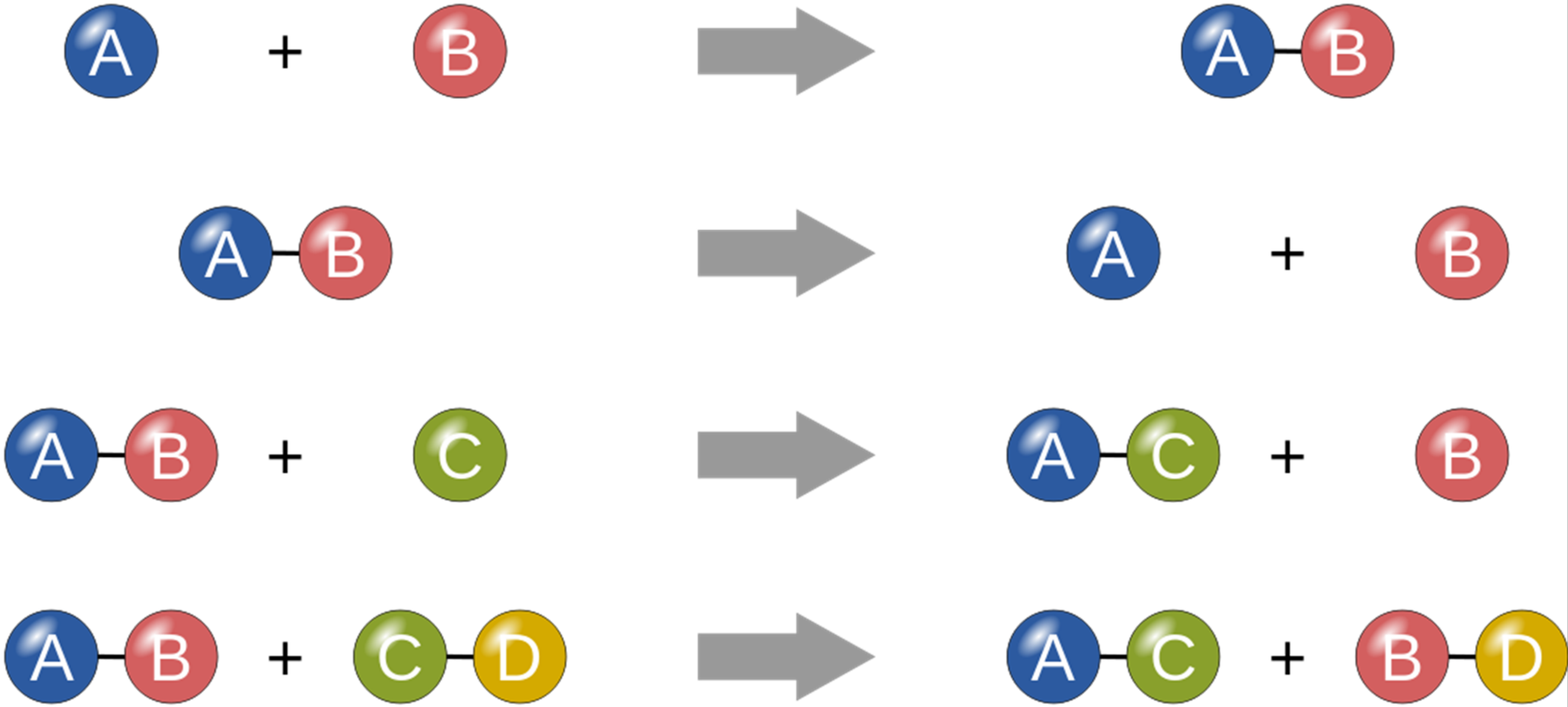
Classification of chemical reactions

1. **Synthesis reactions:** two or more reactants unite to form a single product.
2. **Decomposition reactions:** a single reactant is broken down into two or more products.
3. **Single replacement reactions:** a single free element replaces another element in a compound.
4. **Double replacement reactions:** two compounds react and exchange elements.

5. **acid - base reactions**

6. **redox reactions**

Classification of chemical reactions



Acid-base reactions

An **acid-base reaction** is a chemical reaction in which an **acid** transfers ***protons*** (hydrogen atoms that have lost an electron, H^+) to a **base**. These chemical reactions produce ***water*** and a ***salt***.

Example:

$$HCl + NaOH \rightarrow NaCl + H_2O$$

These reactions are also called **neutralisation reactions** since the acid and base react to neutralize each other's properties.

Acid-base reactions are usually ***exothermic***, i.e., they release energy as heat.

Acid-base reactions

Acids are chemical substances with the following properties:

- a sour taste
- react with bases to produce water and a salt
- react with some metals to liberate hydrogen
- conduct electricity

Examples:

acetic acid (found in vinegar), hydrochloric acid (found in gastric acid in the stomach), and acetylsalicylic acid (aspirin).

Acid-base reactions

Bases (also known as ***alkalis***) are chemical substances with the following properties:

- have a slippery feeling
- react with acids to produce water and a salt
- conduct electricity

Examples:

ammonia, lye (caustic soda), and sodium bicarbonate.

Changes in matter

Acid-base reactions

pH is a numeric scale used to specify the ***acidity*** or ***alkalinity*** of a solution.

The **pH scale** varies from 0 to 14:

- solutions with ***pH < 7*** are ***acidic***.
- solutions with ***pH > 7*** are ***alkaline***.
- solutions with ***pH = 7*** are ***neutral***.

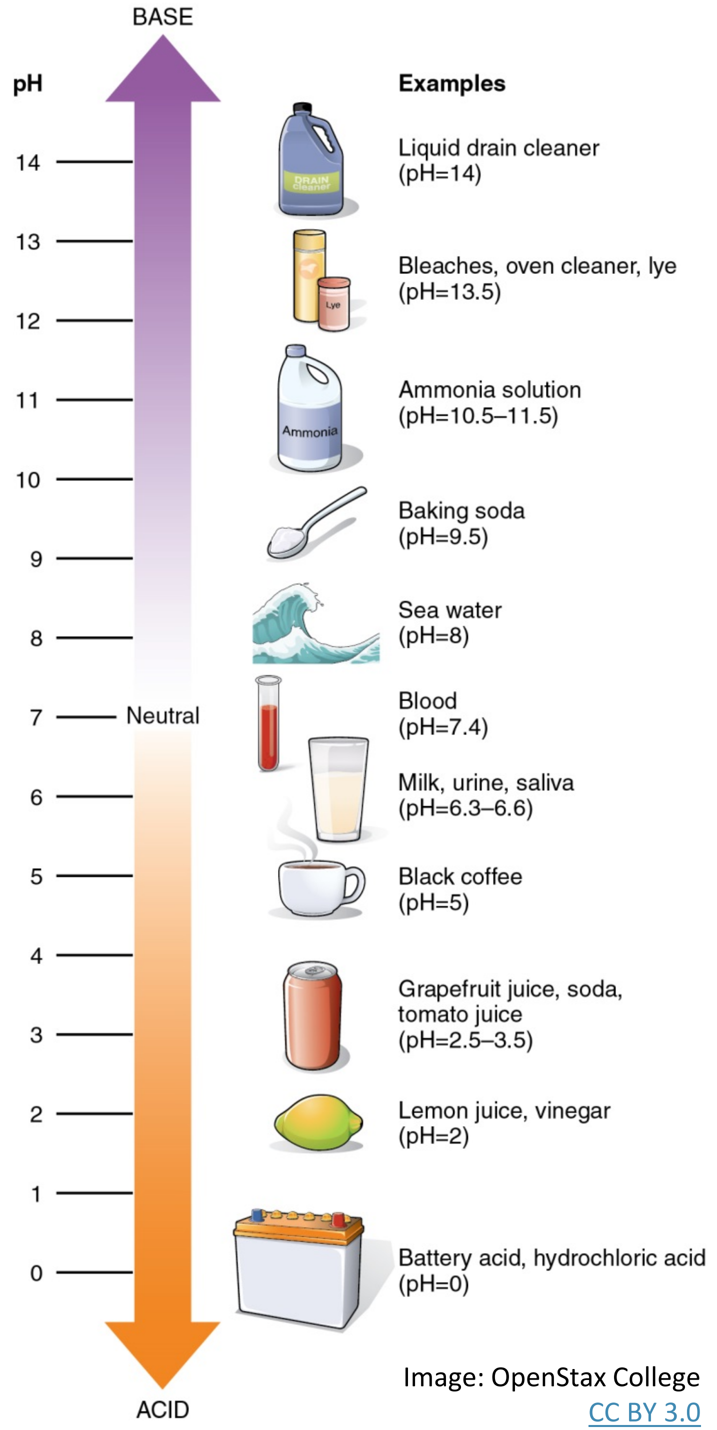


Image: OpenStax College

Acid-base reactions

Example:

Depending on the ground's pH, the flowers of the Hydrangea (also known as hortensia) can be pink (pH > 7) or blue (pH < 7).

Image: www.ForestWander.com

Image: Raul654

Redox reactions

A **redox reaction** (also known as ***reduction-oxidation reaction***) is a chemical reaction that involves the transfer of ***electrons*** between chemical species.

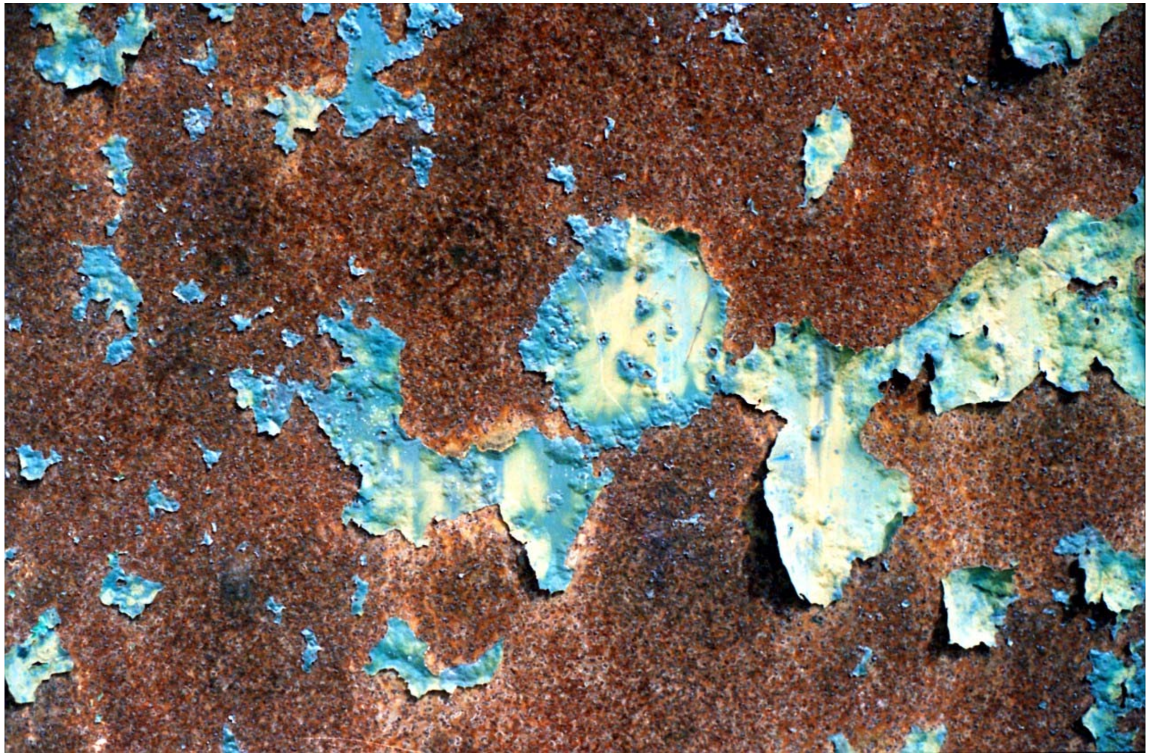
- **Oxidation** is the loss of electrons by a chemical species. The chemical species from which the electron is stripped is called ***reductant***.
- **Reduction** is the gain of electrons by a chemical species. The chemical species to which the electron is added is called ***oxidant***.

Both oxidation and reduction reactions occur simultaneously: the reductant loses electrons and is oxidized, and the oxidant gains electrons and is reduced.

Changes in matter

Redox reactions

Example:



$$4Fe + 3O_2 \rightarrow 2Fe_2O_3$$

Redox reactions – combustion

Combustion is a exothermic ***redox reaction*** between a fuel and an oxidant (usually atmospheric oxygen).

Image: Fir0002

Example:

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4\, H_2O$$

In the combustion of hydrocarbons, carbon dioxide and water are released.

Redox reactions – voltaic cell

Electric batteries, which consist of two or more **voltaic cells**, obtain electrical energy from ***redox reactions***.

Voltaic cells usually consist of zinc and copper submerged in a solution. Since zinc loses electrons more readily than copper, placing them in separate solutions of their salts makes electrons to flow through an external wire from the zinc to the copper, and thus producing an electric current.

Image: Asim18

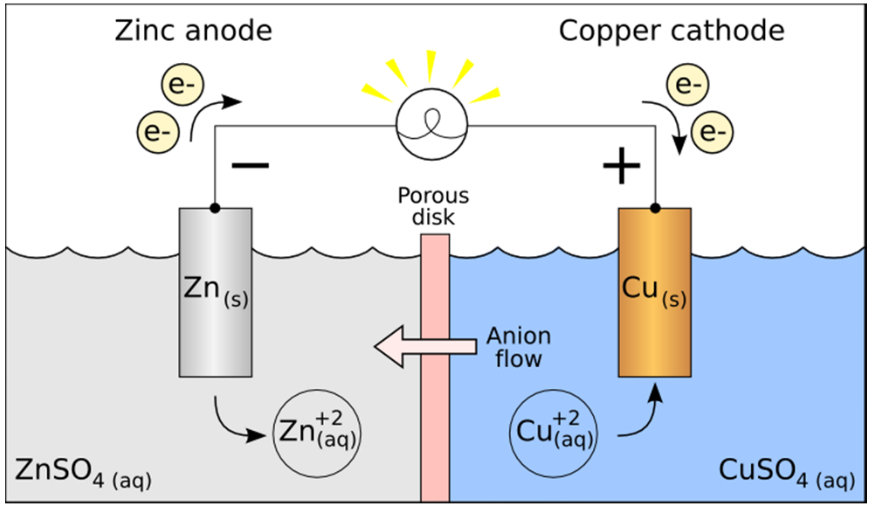


Image: Ohio standard at English Wikipedia/Burpelson AFB